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Spatial variability of production and bromatological composition of *Brachiaria* and *Panicum* according to the soil chemical attributes in a silvipastoral system with eucalyptus

Nilton Eugénio Mário[1], Adriany Rodrigues Corrêa[2], Rafael Montanari[1], Tatiane Carla Silva[3], Anderson Secco dos Santos[4]

[1] Universidade Estadual Paulista "Júlio de Mesquita Filho", Campus de Jaboticabal, Jaboticabal, São Paulo, Brasil. E-mail: nilton.mario@unesp.br, r.montanari@unesp.br

[2] Universidade Estadual Paulista "Júlio de Mesquita Filho", Campus Ilha Solteira, Ilha Solteira, São Paulo, Brasil. E-mail: adriany@agronoma.eng.br

[3] Universidade de São Paulo, Ribeirão Preto, São Paulo, Brasil. E-mail: tcs.agronomia@gmail.com

[4] Universidade Federal da Grande Dourados, Dourados, Mato Grosso do Sul, Brasil. E-mail: anderson.ambiente@gmail.com

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ABSTRACT

The variability of the soil chemical attributes in an area where woody crops are integrated with forage is quite complex, so it is important to understand the distribution of these soil attributes and their correlation with the forage yield. This study aimed to analyze the spatial variability of the production and bromatological composition of *Brachiaria* and *Panicum* forage species according to the soil chemical attributes when cultivated in a silvopastoral system integrated with eucalyptus to optimize the forage yield and nutritional quality of the forage in this multiple-use system. The study was conducted in the municipality of Ribas do Rio Pardo (MS) in the 2011/2012 crop season, where linear and spatial correlations were analyzed between attributes of eucalyptus, forage plants, and the chemical attributes of a Neossolo Quartzarênico (pH, organic matter (OM) and organic carbon (OC) contents, and carbon stock (CS)) at two soil layers: 0.00-0.10 and 0.10-0.20 m. A geostatistical grid with 72 sample points was used. Spatially, eucalyptus height can be estimated by cokriging with OM, and cellulose by cokriging with pH. OM contents above 6 g cm^{-3} indicated sites with the highest eucalyptus heights. On the other hand, pH values below 4.3 indicated sites with the highest cellulose content for the forage plants. Using geostatistics is technically feasible for creating specific management zones in the eucalyptus forage silvopastoral system.

Keywords: Geostatistics, Soil management and conservation, Forest sustainability.

Variabilidade espacial da produção e composição bromatológica de *Brachiaria* e *Panicum* em função dos atributos químicos com eucalipto em sistema silvipastoril

RESUMO

A variabilidade dos atributos químicos do solo em uma área de integração de culturas lenhosas em associação com forrageiras é bastante complexa, assim, é de grande importância compreender a distribuição destes atributos do solo e sua correlação sobre a produtividade. Nesse sentido, o objetivo do trabalho foi analisar a variabilidade espacial da produção e a composição bromatológica de espécies forrageiras *Brachiaria* e *Panicum*, em função dos atributos químicos do solo, quando cultivadas em um sistema silvipastoril integrado com eucalipto, visando otimizar a produtividade e a qualidade nutricional das forragens nesse sistema de uso múltiplo. O trabalho foi desenvolvido no município de Ribas do Rio Pardo (MS) no ano agrícola 2011/2012, onde foram analisadas as correlações lineares e espaciais entre atributos do eucalipto, das plantas forrageiras e dos atributos químicos de um Neossolo Quartzarênico os quais foram: pH, teor de matéria orgânica (MO), carbono orgânico (CO) e estoque de carbono (EC) em duas profundidades: 0,00-0,10 e 0,10-0,20 m. Para isso, foi utilizada uma malha geoestatística com 72 pontos amostrais. Espacialmente, a altura do eucalipto pode ser estimada por meio da co-krigagem com a MO, e a celulose por meio do pH. Teores de MO acima de 6 g cm^{-3} indicaram sítios com as maiores alturas para o eucalipto. Já, valores de pH abaixo de 4,3 indicaram sítios com o maior teor de celulose para as forrageiras. A utilização da geoestatística é tecnicamente viável para criação de zonas específicas de manejo no sistema silvipastoril entre eucalipto e forrageiras.

Palavras-chave: Geoestatística, Manejo e conservação do solo, Sustentabilidade florestal.

1. Introduction

Livestock production faces significant challenges related to sustainable pasture management, especially in integrated systems that aim to optimize the use of natural resources (Silva and Silva, 2020). The silvopastoral system, which combines trees and pastures in the same area, has emerged as a promising solution for improving pasture yield and sustainability (Oliveira et al., 2023). This system provides economic diversification for producers and promotes soil conservation, reduced erosion, and increased biodiversity (Oliveira et al., 2023).

Eucalyptus, in particular, has been widely used in silvipastoral systems to improve soil quality provide shade for livestock and due to its rapid growth rate, high biomass production, and ability to adapt to different environmental conditions (Cordeiro and Balbino, 2019). The integration of eucalyptus in silvipastoral systems can significantly influence the chemical attributes of the soil, such as pH, nutrients, and organic matter, which in turn affect the production and quality of pastures, requiring a detailed analysis of the spatial variability of production and the bromatological composition of forage species, such as *Brachiaria* and *Panicum* (Cordeiro and Balbino, 2019).

Spatial variability in forage production is an important aspect to consider in silvopastoral systems (Amaral et al., 2021; Compagnon et al., 2020). The heterogeneous distribution of nutrients and resource competition between trees and pastures can result in distinct spatial patterns in forage production. Many factors can influence this variability, including soil characteristics, climatic conditions, and management practices (Amaral et al., 2021). Analysis of this variability can provide valuable information on optimizing pasture management and improving silvopastoral systems efficiency (Diego, 2024). Furthermore, understanding the spatial interaction between eucalyptus and pastures can help identify productive zones and allocate resources more efficiently (Guerino et al., 2022).

Brachiaria and *Panicum* are two of the main forage species used in grazing systems in Brazil due to their high adaptability and nutritional value (Amorim, 2023). The production and bromatological quality of these species can vary significantly depending on the chemical attributes of the soil, which are influenced by the presence of trees such as eucalyptus (Santos et al., 2023). The chemical attributes of the soil, including the availability of essential nutrients such as nitrogen, phosphorus, and potassium, play a crucial role in the growth and quality of forage crops (Silva et al., 2020). Eucalyptus can alter these attributes over time, affecting the spatial variability in pasture production and bromatological composition (Santos et al., 2023).

The bromatological composition of pastures is a determining factor in the nutritional quality of animal diets (Voltolini and Gois, 2021). The presence of eucalyptus can influence the composition of pastures, altering the concentration of essential nutrients and the digestibility of forage (Silva et al., 2022). The bromatological analysis of *Brachiaria* and *Panicum* species under different conditions of interaction with eucalyptus is essential to assess the impact of this practice on the nutritional value of pastures and animal health and performance (Voltolini and Gois, 2021; Santos et al., 2023).

Understanding the spatial variability in the production and bromatological composition of pastures is essential for implementing more effective management practices in silvopastoral systems (Compagnon et al., 2020; Voltolini and Gois, 2021; Amaral et al., 2021). Previous studies have shown that spatial variability can be influenced by several factors, including tree distribution, soil chemical attributes, and forages (Amaral et al., 2021; Compagnon et al., 2020). However, the specific combination of eucalyptus and forage species such as *Brachiaria* and *Panicum* in silvipastoral systems is still little explored, requiring further investigation to understand these interactions better.

In addition, the sustainable management of silvopastoral systems requires consideration of the environmental and economic impacts associated with the integration of trees and pastures (Costa et al., 2022; Diego, 2024). Analysis of spatial variability and bromatological composition can help identify management practices that maximize these systems' economic and environmental benefits (Voltolini and Gois, 2021; Amaral et al., 2021). Implementing management strategies based on accurate data can improve pasture yield, soil quality, and the overall sustainability of the system (Silva et al., 2023).

Research into the spatial variability of production and bromatological composition in silvipastoral systems with eucalyptus is relevant to modern agriculture. The results can provide valuable insights for developing more effective management practices in silvipastoral systems, contributing to the sustainability and efficiency of livestock production. More detailed and specific studies are needed to develop practical recommendations for different regional contexts and soil and climate conditions.

Finally, the integration of eucalyptus in silvopastoral systems represents a promising opportunity for the development of more sustainable and productive agricultural practices and can offer additional benefits such as reducing pressure on pastures and improving soil structure (Santos et al., 2023). However, these benefits depend on how the system is managed and the specific characteristics of the environment. Analyzing spatial variability in the production and bromatological composition of forage is essential to identify management practices that maximize the benefits of the silvopastoral system (Amaral et al., 2021). This includes evaluating different spatial arrangements and densities of eucalyptus plantations and implementing strategies to minimize the negative impacts of competition between trees and pastures (Compagnon et al., 2020).

In this context, this study aims to analyze the spatial variability of the production and bromatological composition of *Brachiaria* and *Panicum* forage species according to the soil chemical attributes in an area of silvopastoral system integrated with eucalyptus to optimize the yield and nutritional quality of the forage in this multiple-use system.

2. Material and Methods

The experiment was conducted in Ribas do Rio Pardo (MS), at 20º26'34" S and 53º45'32" W. The average annual rainfall is 1,500 mm, and the average annual temperature ranges from 19 ºC to 25 ºC. According to the Koeppen classification, the climate is Aw-type, characterized as tropical humid with a rainy season in summer and a dry season in winter. Data on rainfall and average, minimum, and maximum temperature (October 1, 2011 to September 30, 2012) were recorded by the Agritempo weather database (Figure 1).

An area of approximately one hectare, previously cultivated for more than 20 years with brachiaria (*Brachiaria* (*Syn. Urochloa*) *decumbens*, cultivar Basilisk), was prepared for the commercial cultivation of eucalyptus. At the end of April to mid-May 2008, this area began with the application of glyphosate for the desiccation of Basilisk grass (*B. decumbens*, cultivar Basilisk), followed by subsoiling to a depth of 0.60 m and then furrowing and fertilizing. Three years after planting the eucalyptus, three species of forage were sown: *B. brizantha* (cultivar Marandú), *B. brizantha* (cultivar Piatã), and *Panicum maximum* (cultivar Massai) continuing the management of the area.

Before the experiment, the soil was chemically characterized (Table 1) in the 0.00-0.20 and 0.20-0.40 m soil layers. After the analyses, the soil, which is the same as the one in which the experimental grid was installed, was classified as Neossolo Quartzarênico (Entissolo Vermelho Distroférrico), with flat relief and the following chemical characteristics.

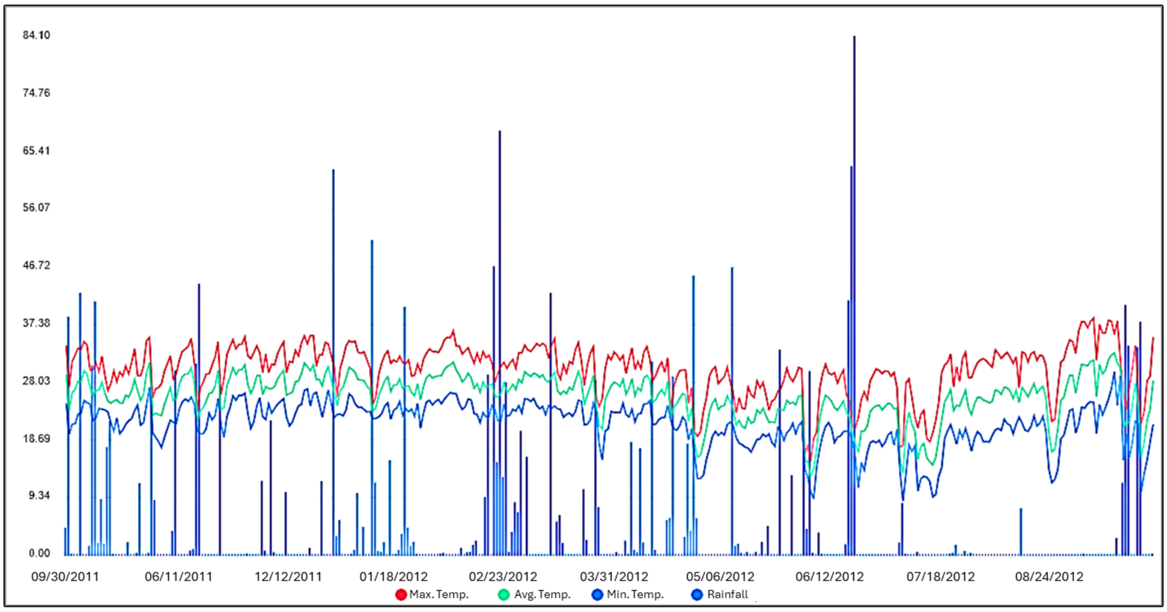


Figure 1. Climatic data recorded during the experimental period - Ribas do Rio Pardo (MS), MG. **Source:** Agritempo, (2024).

Table 1. Chemical characterization of the soil in the experimental area

OM	P	pH	K^+	Ca^{2+}	Mg^{2+}	H^++Al^{3+}	Al^{3+}	SB	CEC	V	m
mg dm^{-3}			mmol$_c$ dm^{-3}							%	
11 & 8	8 & 3	4 & 4.1	0.2 & 0.1	1 & 0	1 & 0	28 & 23	9 & 6	19 & 9	47 & 32	40 & 28	32 & 42

Source: Author

Limestone Filler (ECCE 92.25%) increased base saturation to 60%. After this correction, the tree species were planted using *Eucalyptus camaldulensis* seedlings from Reflorestadora Ramires commercial nursery in Ribas do Rio Pardo, MS. For planting, 40×40×40 cm holes were dug, and chemical fertilization was carried out, following the recommendation to apply 50 kg of nitrogen per hectare (N ha^{-1}) in the form of ammonium sulfate (NH_4SO_4), 70 kg of P_2O_5 per hectare (P_2O_5 ha^{-1}) in the form of Yoorin thermophosphate, and 80 kg of potassium per hectare (K_2O ha^{-1}) in the form of potassium chloride, previously mixed into the soil before transplanting the seedlings (Cantarutti et al., 1999).

The seedlings were transplanted into the field during the sowing period of the three forage species, maintaining a spacing of 1.5 m between the forages and the eucalyptus rows. Additionally, 30 days after emergence, topdressing fertilization was conducted by applying a further 50 kg of nitrogen per hectare as urea (Cantarutti et al., 1999). During the establishment of the tree crop and forage species, the pastures were managed with small animals under light grazing.

All the attributes of the plants (eucalyptus and forage) and the soil were assessed in samples collected around each sampling point of the experimental grid, which contained 72 points with irregular spacing. Sampling took place in April 2012. The dendrometric characteristics assessed in the *Eucalyptus camaldulensis* were tree height (HEIGHT) using a hypsometer and the circumference at breast height (CBH), measured at the height of 1.30 m from the ground using a tape measure.

A sample area of 0.25 m^2 (demarcated with a metal template) was considered for assessing the dry matter mass of the forage (DMF). The material within the area was cut 15 cm from the soil surface using garden shears, then packed in a paper bag, weighed using a digital scale, and placed in an oven (65 ºC until constant mass). Laboratory analyses were also conducted to determine the levels of crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), in vitro digestibility of organic matter (IVDOM), and cellulose according to the methodology described by Silva and Queiroz (2002).

The soil attributes assessed were hydrogen potential (pH), organic matter (OM) and organic carbon (OC) contents, and carbon stock (CS), collected from the 0.00-0.10 m and 0.10-0.20 m soil layers. The soil samples were air-dried, crumbled, and passed through 2 mm sieves, characterizing fine air-dried soil (FADS), and sent for analysis. The methodology used to determine the chemical attributes followed the determinations of EMBRAPA (2018).

For each attribute studied, classical descriptive statistical analysis was conducted using SAS® software (Schlotzhaver and Littell, 1997), where the mean, median, minimum and maximum values, standard deviation, coefficient of variation (CV), kurtosis, and asymmetry were calculated. The frequency distribution of the data was also analyzed. The Shapiro & Wilk test (1965) at 1% was used to test the hypothesis of normality of the attributes.

Geostatistical analysis was performed using *Gamma Design Software* 7.0 (GS^+ 2004). Spatial dependence was analyzed by calculating the semivariogram, and for those that showed spatial interdependence, the crossed semivariograms were also calculated based on the stationarity assumptions of the intrinsic hypothesis. Simple semivariograms were fitted for the dendrometric characteristics of *Eucalyptus camaldulensis*, the yield and bromatological composition of the forage plants, and the chemical attributes of the soil. Therefore, for each attribute, the nugget effect (C_o), the range (A_o), and the plateau ($C_o + C$) were estimated. For the modeling of kriging and cokriging maps, *Gamma Design Software* 7.0 was again used to analyze the spatial dependence and interdependence between the attributes.

3. Results and Discussion

Using the classification proposed by Pimentel Gomes and Garcia (2002), according to the magnitude of its coefficient of variation (CV), the variability of each attribute was classified and determined by class as low ($CV \leq 10\%$), medium ($10\% < CV \geq 20\%$), high ($20\% < CV \leq 30\%$), and very high ($CV > 30\%$). Table 2 shows the descriptive analysis of the attributes studied, where height (HEI) showed medium variability with a CV of 11.5%, corroborating Lima et al., (2019), who found a median value of 18.23% when studying the characteristics of Entisol treated with pulp residue and fertilizer in eucalyptus plantations, but differing from Vasconcelos et al., (2021) who found a high variability value of around 22.04% when assessing the performance of eucalyptus clones in two environmental conditions to measure the genotype x environment interaction.

Concerning the forage, DMF had a very high CV, while CP, IVDOM, and CELLULOSE showed medium variability, and NDF and ADF had a low CV, with 4.4% and 9.5% (Table 2). The high CV observed for DMF was lower than the 59.7% found by Dalchiavon et al., (2017), evaluating the yield and quality of *Brachiaria* (*Syn. Urochloa*), using a 120-point mesh in a Latossolo Amarelo in the Cerrado. The CV of 13.8% for CBH indicated that the variability in plant diameter is medium, suggesting that plant CBH measurements are not highly dispersed, but there is some variability.

Table 2. Initial descriptive analysis of the dendrometric characteristics of *Eucalyptus camaldulensis* and yield and bromatological composition of the *Brachiaria* and *Panicum* genera forage plants.

Attribute(a)	Descriptive statistical measures									
									Probability	
	Average	Median	Max.	Min.	Stan. Dev.	Variation	Kurt.	Asymm.	Pr<w	FD
Eucalyptus attributes										
CBH (cm)	46.38	46.06	66.42	29.35	6.40	13.8	1,217	0.118	0.3079	NO
HEIGHT (m)	17.25	17.20	19.95	13.66	1.98	11.5	-	-0.281	0.0001	IN
Forage attributes										
DMF (kg ha^{-1})	2990.67	2652.00	6680.00	896.00	1356.76	45.4	0.682	1,059	0.0001	IN
CP (%)	6.80	6.82	8.92	4.61	1.00	14.7	-	-0.069	0.1714	NO
NDF (%)	76.25	76.06	81.85	68.36	3.33	4.4	-	-0.250	0.1718	NO
ADF (%)	39.46	38.67	45.23	31.86	3.76	9.5	-	-0.193	0.0026	IN
IVDOM (%)	48.45	48.95	60.04	37.30	5.89	12.2	-	0.117	0.1787	NO
CELLULOSE	29.73	28.39	35.87	22.49	3.63	12.2	-	-0.055	0.0001	IN

(a) Circumference at breast height (CBH), plant height (HEI), dry matter mass of forage (DMF), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), in vitro digestibility of organic matter (IVDOM), cellulose (CELLULOSE); (b) Frequency distribution (FD), being normal (NO) or indeterminate (IN).

While the standard deviation of 6.40 cm for CBH revealed considerable variation in plant diameter, most attributes showed an indeterminate distribution (IN), meaning that the data distribution does not follow a clear pattern and may not be normal or symmetrical. However, the CBH and CP attributes were classified as normal (NO), where most values are concentrated around the average, with symmetry on both sides.

CBH showed a normal frequency distribution, with an asymmetry coefficient of 0.118 and a kurtosis of 1.217. However, CBH was significant at 5% probability using the Shapiro and Wilk (1965) normality test since its respective probability was 0.3079 (Table 2). HEIGHT showed an indeterminate frequency distribution with an asymmetry coefficient of -0.281 and a kurtosis of -1.324, which was insignificant at 5% probability using the normality test since its probability was 0.0001.

The average values for HEIGHT and CBH were 17.25 m and 46.38 cm, respectively (Table 2). Figueiredo et al., (2020a), evaluating the height growth of different eucalyptus hybrids at 2 years of age, obtained heights ranging from 10.44 to 14.16 m and CBHs ranging from 8.69 to 10.40 cm, which are almost similar to the heights of the present study due to the close age (3 years) of the eucalyptus trees. However, this minimal difference in plant age may partially explain the variation in heights observed since older plants tend to be naturally taller. However, there is a notable difference in the CBH values. This suggests that, although the heights were almost similar, other factors may have influenced the diametrical growth of the eucalyptus, such as planting density, competition for resources, or specific characteristics of the hybrids studied.

The average DMF (2990.67 kg ha^{-1}) was relatively low (Table 2) when compared to the yield of 20.37 t ha^{-1}, highlighting its high yield potential, as reported by Santos et al., (2023) working with *B. decumbens*. These plants are often used to cover the soil and recycle nutrients, thanks to their robustness and versatility in adapting to different soil and climate conditions and their high productive capacity (Santos et al., 2023). Nascimento and Almeida (2020) found an average yield of 8,819 kg ha^{-1} when evaluating the agronomic characteristics of 11 tropical forage grasses of the genera *Urochloa* (*Sin. Brachiaria*.) and *Panicum* in the conditions of southwestern Goiás, in a grid containing 440 points on a Latossolo Vermelho Distrófico. Therefore, the productivity of DMF was considered high, taking into account the presence of eucalyptus, even with the shading of the tree canopy, the forage yield did not decrease.

The average CP content of the forage was 6.80% (Table 2), which was lower than the rate of 11.35% obtained by Figueiredo et al., (2020b) when they evaluated the use of laying hen manure in the contribution of litter and nutrients in *Urochloa brizantha* forage production systems. According to the authors, the high CP content obtained in tropical forage plants is due to the correct application of organic residues, which makes it possible to achieve quantitative and qualitative forage production levels that are statistically equal to those of chemical fertilization and also promote the increase of organic material in the soil. According to Guo et al., (2022), forages with a CP content of less than 7% reduce ruminants' consumption of dry matter of forage. This is due to the lower digestibility caused by the deficiency of nitrogen, which is essential for rumen bacteria and compromises fermentation and the absorption of essential nutrients.

The average values for NDF, ADF, and IVDOM (Table 2) were 76.25%, 39.46%, and 48.45%, respectively. These results show that the forage has high levels of NDF and ADF, as indicated by Kılıç et al., (2021), contributing to a reduction in forage consumption and a decrease in digestibility. Therefore, low digestibility and lower intake reflect ruminants difficulty processing and enjoying forage due to its high load of total fiber and indigestible components. Adjustments in management or type of forage may be necessary to improve feed efficiency.

However, the high NDF (76.25%) indicates that the forage is high in fiber, making it difficult for ruminants to chew and digest, which can reduce the consumption and efficiency of the diet. The moderate ADF (39.46%) reduces the digestibility of the forage, which results in fewer nutrients being available to the animals. The IVDOM of 48.45% shows that less than half of the organic matter in the forage is digested by ruminants.

This low value reflects the difficulty of digestion due to the high contents of NDF and ADF. In the case of the chemical attributes of the soil, pH_1 (4.21) and pH_2 (4.14) show the very high acidity of the soil ($pH < 5.0$), with a low OM content (5.85 and 13.22), according to Barbieri et al., (2020). The variability of pH_1 and pH_2 was low, with a CV between 0.02% and 5.91%. On the other hand, the OM_1, OM_2, OC_1, OC_2, CS_1, and CS_2 attributes had very high CVs, ranging from 34.40 to 51.76% (Table 3).

According to Silva et al., (2020), the variability of the soil chemical attributes is related to changes caused by irregular fertilization and liming and due to the high diversity around the average between the chemical attributes in the area evaluated. The heterogeneity observed in the area may be related to the variability of the nutrient levels in the soil absorbed by the plants, providing greater development of the forage plants, reflecting a greater accumulation of OM in some regions, influencing the high CV observed for these attributes.

The average organic carbon (OC) values in Table 3 indicate that the highest OC content was found in the topsoil (OC_1), with 7.65 g dm^{-3}. As the soil depth increased, the organic carbon content decreased, reaching 3.44 g dm^{-3}. This is because organic matter tends to accumulate on the surface of the soil due to the decomposition of plant residues and other organic materials. Martins et al., (2022) evaluated the linear and spatial variability of eucalyptus dendrometric attributes correlated with the attributes of a Latossolo in the Brazilian Cerrado and found a lower OC value than this study, with 6.58 g dm^{-3}.

These results suggest that the specific conditions of the study site influence OC levels, highlighting the importance of considering environmental variability and management practices when assessing soil health and quality. The presence of forage plants and the cultivation of eucalyptus contributed to a higher OC content at the surface since most of the roots of these plants are located in the topsoil. Thus, these systems can help maintain or increase soil OC, highlighting evergreen tree species positive influence in the iCLF (Integrated crop-livestock-forestry) system. The results show that the average carbon stock value in the two soil layers studied (CS_1 and CS_2) was 11.08 t ha^{-1} and 5.38 t ha^{-1}, respectively.

These values are significantly higher than the 3.7 t ha^{-1} reported by Lima et al., (2020), who measured the soil respiration of Caatinga vegetation and degraded pasture to verify the effect of changes in land use on soil respiration in a Luvissolo Crômico. This suggests that the soil conditions or management practices in the areas studied promote greater carbon retention. Table 4 shows the parameters of the simple semivariograms for the plant attributes. The results indicate that all the attributes studied showed spatial dependence, fitting the exponential semivariogram model.

Table 3. Descriptive analysis of the soil chemical attributes in the 0.00-0.10 m and 0.10-0.20 m layers of a Neossolo Quartzarenico

Attribute [a]	Descriptive statistical measures									
	Average	Median			Standard Deviation				Probability	
			Maximum	Minimum		Variation	Kurtosis	Asymmetry	Pr<w	FD
pH_1 ($CaCl_2$)	4.21	4.1	4.9	3.9	0.25	5.91	1.306	1.412	0.0001	IN
pH_2 ($CaCl_2$)	4.14	4.1	4.5	3.9	0.13	0.02	-0.005	0.588	0.0001	IN
OM_1 (g dm^{-3})	13.22	12.0	26.0	2.0	4.61	34.84	0.268	0.547	0.0326	IN
OM_2 (g dm^{-3})	5.85	5.0	14.0	1.0	2.86	48.94	0.411	0.733	0.0068	IN
OC_1 (g dm^{-3})	7.65	7.1	15.1	1.2	2.63	34.40	0.363	0.530	0.0726	NO
OC_2 (g dm^{-3})	3.44	3.2	8.6	0.5	1.76	51.20	0.526	0.801	0.0106	IN
CS_1 (t ha^{-1})	11.08	9.9	22.9	1.9	3.97	35.82	0.626	0.665	0.0189	IN
CS_2 (t ha^{-1})	5.38	4.8	13.6	0.7	2.78	51.76	0.591	0.829	0.0096	IN

[a]) Hydrogen potential (pH_1 and pH_2), organic matter content (OM_1 and OM_2), organic carbon content (OC_1 and OC_2), carbon stock (CS_1 and CS_2) collected in the 0.00-0.10 $m_{(1)}$ and 0.10-0.20 $m_{(2)}$ soil layers; [b] Frequency distribution (FD), being normal (NO) or indeterminate(IN).

This finding is consistent with existing literature, as Lima et al., (2022) mentioned, who point out that spherical and exponential models are often applied to soil and plant attributes. The research by Dalchiavon et al., (2017) corroborates these results by finding the exponential model suitable when studying the crude protein (CP) of the forage *U. decumbens*. This consistency suggests that the exponential model is robust and suitable for representing the spatial variability of attributes in agricultural studies.

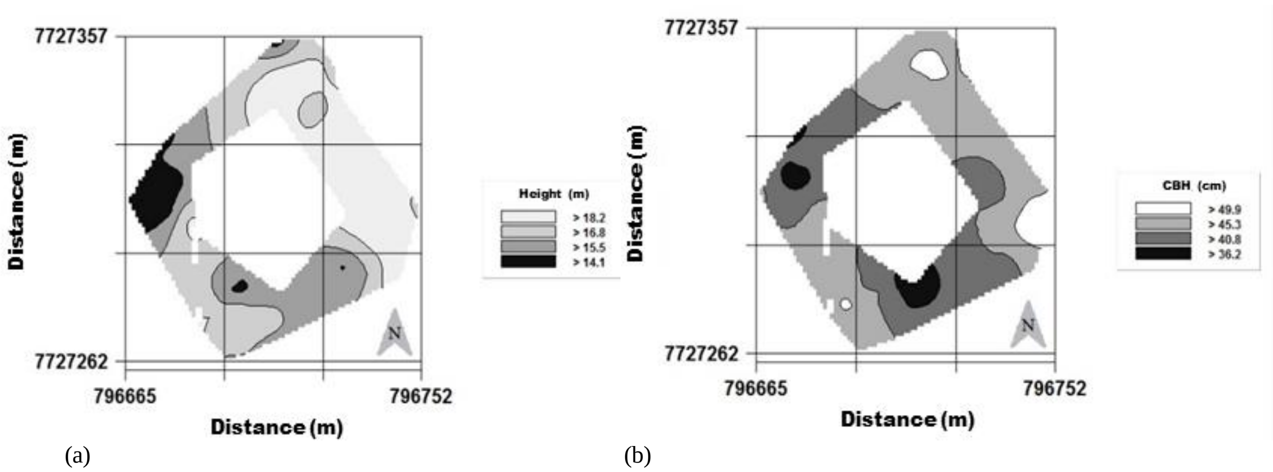
Concerning the performance of the semivariograms, the highest coefficient of spatial determination (r^2) observed for fitting the model was 0.852 when modeling the spatial dependence of ADF, and the lowest coefficient was 0.464 when modeling the spatial dependence of DMF (Table 3). Therefore, ADF was the plant attribute with the best semivariogram fit, with a spatial dependence evaluator (SDE) of 89%, showing high spatial dependence. The increasing relationship of the ranges (m) was as follows: CELLULOSE (11.1), DMF (12.0), ADF (14.0), CP (14.7), HEI (15.3), IVDOM (15.3), NDF (23.1), and CCH (32.7). Thus, using precision agriculture, the A_0 values used in geostatistical packages in iCLF (silvopastoral system) should not be less than 11.1m.

The kriging maps (Figure 2) show a well-defined spatial distribution of the attributes of the eucalyptus crop in the area evaluated, which made it possible to identify homogeneous zones. The map of HEIGHT (Figure 2a) and CBH (Figure 2b) showed high spatial similarity for practical crop management purposes. It can be seen that between the third and ninth nodes there are the highest HEIGHT and CBH values. Figures 3a and 3b show the maps illustrating the spatial distribution of organic carbon (OC) in layers 1 (OC1) and 2 (OC2), respectively, where the different shades of gray indicate the concentrations of OC, with the darkest areas having the highest concentrations.

Table 4. Parameters of the adjusted simple and cross semivariograms of the dendrometric characteristics of *Eucalyptus camaldulensis* and yield and bromatological composition of forage plants of the *Brachiaria* and *Panicum* genera.

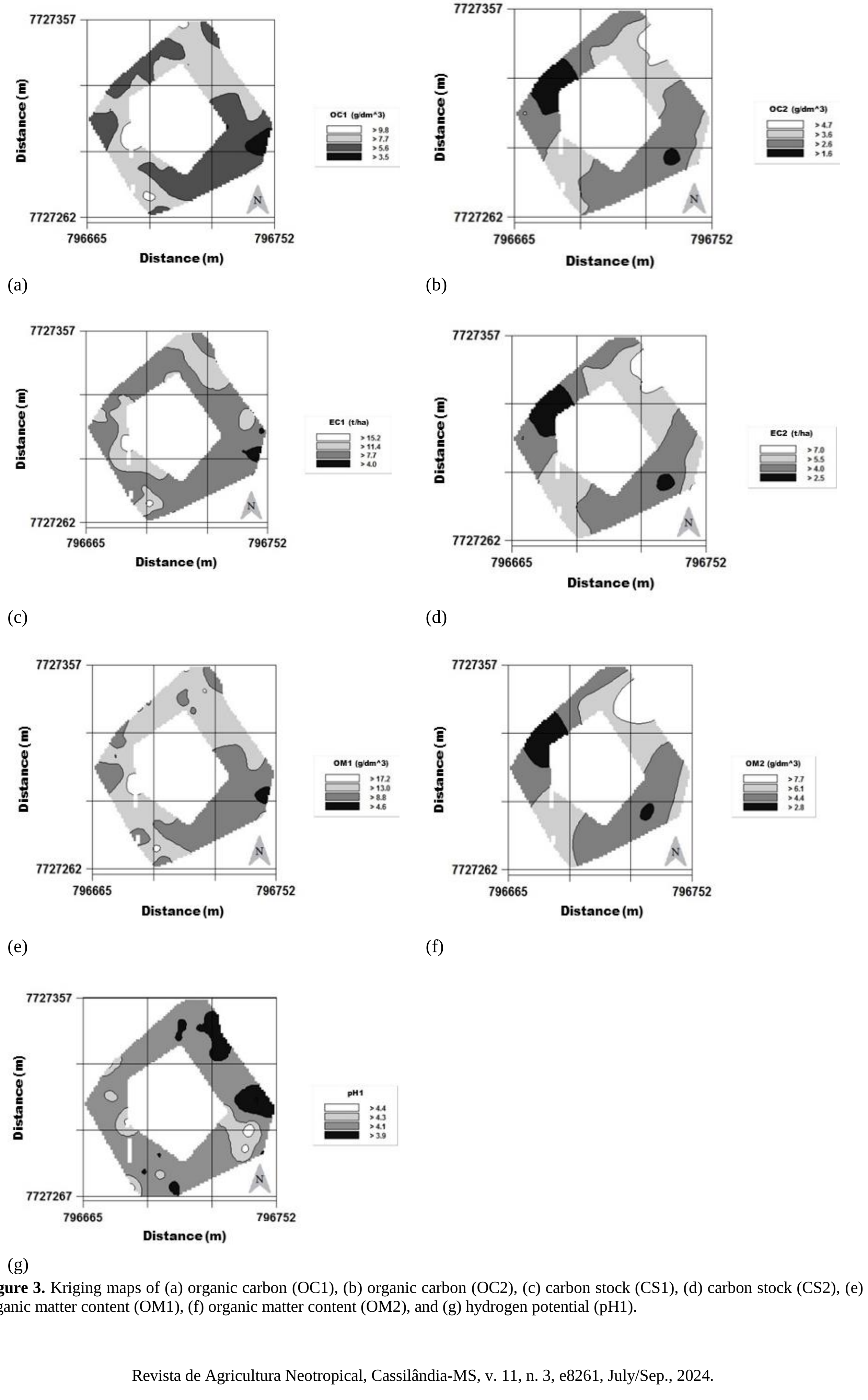
Attributes [(a)]	Parameters							
	Model [(b)]	Nugget effect (C_0)	Level (C_0+C)	Range (A_0)(m)	r^2	SQR [(c)]	Spatial dependence evaluator	
							SDE [(d)]	Class
γ(h) simple plant attributes								
DMF	Exp.(98)	$2.690.10^{5}$	$1.547.10^{6}$	12.0	0.464	$1.440.10^{11}$	82.6	VH
CP	Exp.(91)	$1.130.10^{-1}$	$8.830.10^{-1}$	14.7	0.672	$4.040.10^{-2}$	87.20	VH
CBH	Exp.(108)	1.208.10	3.378.10	32.7	0.827	3.650.10	64.20	HD
HEI	Exp.(114)	$4.340.10^{-2}$	$2.638.10^{-1}$	15.3	0.691	$2.775.10^{-3}$	83.50	VH
NDF	Exp.(73)	4.600	1.096.10	23.1	0.653	6.97	58.00	MD
ADF	Exp.(94)	1.260	1.145.10	14.0	0.852	2.222	89.00	VH
IVDOM	Exp.(66)	3.970	3.134.10	15.3	0.691	$2.775.10^{-3}$	83.50	VH
CELLULOSE	Exp.(68)	1.110	1.083.10	11.1	0.479	1.290.10	89.80	VH
γ(h) cross between plant and soil attribute								
HEI=f(OM_2)	Gau.(61)	$1.780.10^{-1}$	2.481	31.9	0.782	2.09	92.80	VH

(a) Circumference at breast height (CBH), height (HFH), forage dry matter mass (DBM), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), in vitro digestibility of organic matter (IVDOM), cellulose (CELLULOSE). [(b)] exponential (exp), spherical (sph), and pure nugget effect (pne); model followed by a number in brackets, meaning the number of pairs in the first lag. [(c)] Sum of squares of residuals (SQR); [(d)] Spatial dependence evaluator (SDE), being very high spatial dependence (VH), high dependence (HD), and medium dependence (MD).



(a) (b)

Figure 2. Kriging map of (a) height and (b) circumference at breast height (CBH) of the eucalyptus crop.



(a)

(b)

(c)

(d)

(e)

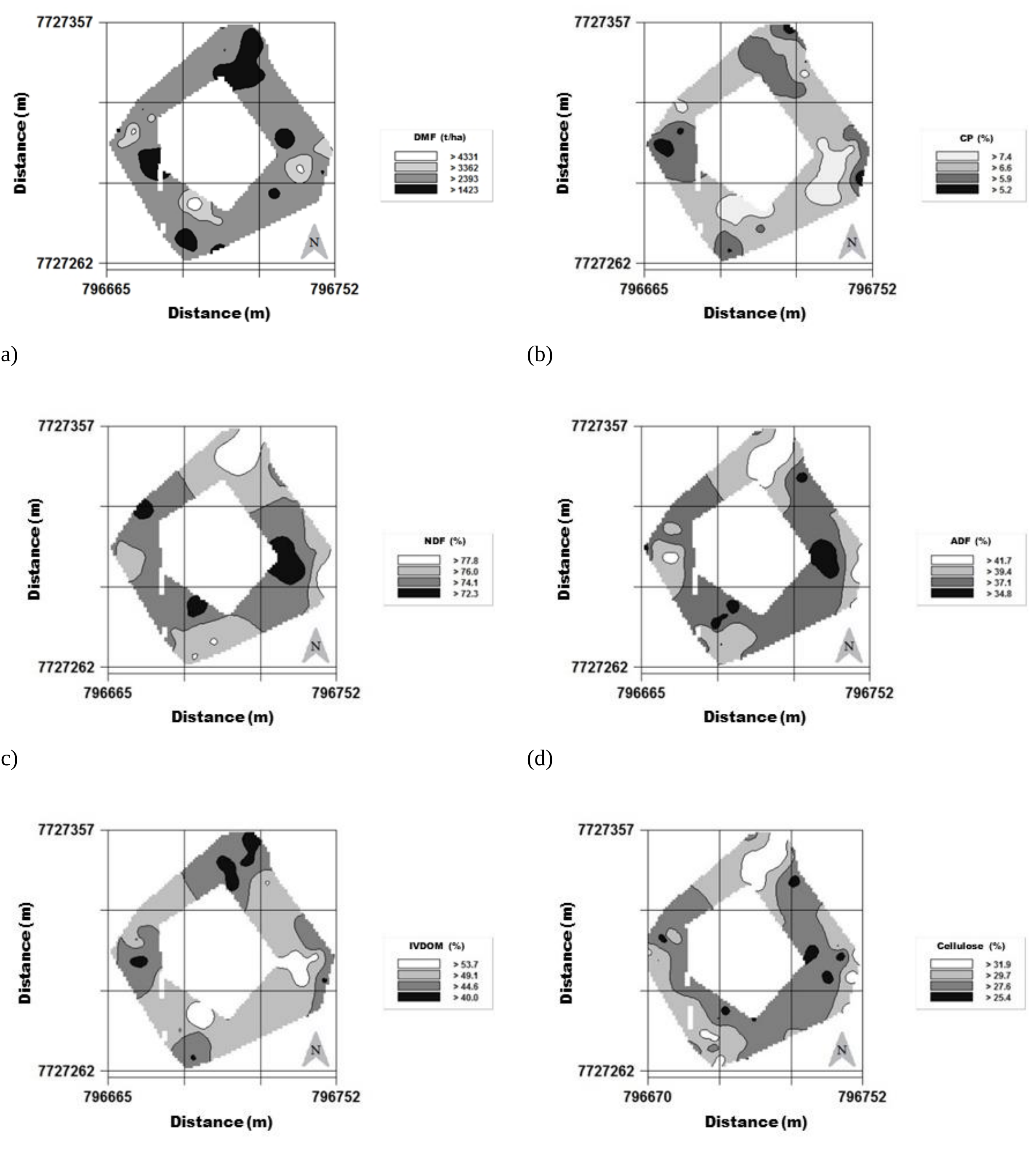
(f)

(g)

Figure 3. Kriging maps of (a) organic carbon (OC1), (b) organic carbon (OC2), (c) carbon stock (CS1), (d) carbon stock (CS2), (e) organic matter content (OM1), (f) organic matter content (OM2), and (g) hydrogen potential (pH1).

As we can observe in Figures 3c and 3d, where the spatial distribution of carbon stock (CS) in layers 1 (CS1) and 2 (CS2) is illustrated, again, the different shades of gray represent the amounts of carbon stored, with the darker areas indicating greater stock. Overall, the spatial analysis of OC and CS in two soil layers reveals heterogeneity in distribution, with variations attributed to factors such as soil type, topography, and land use history.

The surface layer (OC1) generally has a higher concentration of OC due to the deposition of fresh organic matter, while the deeper layer (OC2) may have a lower concentration due to decomposition. However, CS is directly related to the concentration of OC, but depth is also a crucial factor, with the deepest layer (CS2) presenting a greater total stock due to the greater volume of soil, even with a lower concentration of OC. These results highlight the importance of considering spatial distribution and depth when assessing soil carbon, with implications for sustainable land management and climate change mitigation.



(a) (b)

(c) (d)

(e) (f)

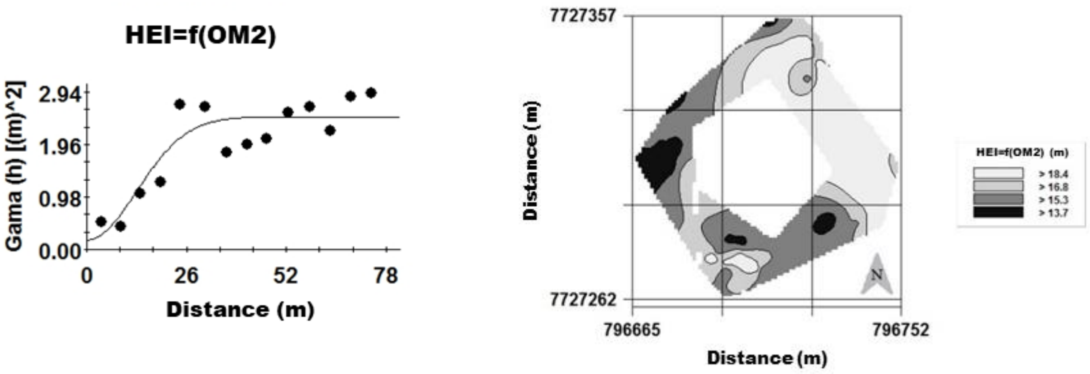
Figure 4. Kriging map of (a) Dry Matter of Forage (DMF), (b) Crude Protein (CP), (c) Neutral Detergent Fiber (NDF), (d) Acid Detergent Fiber (ADF), (e) In vitro Digestibility of Organic Matter (IVDOM), and (f) Forage Cellulose

Concerning the kriging maps of the components of the forage plant (Figure 4), the highest CP values are found in the third, sixth, and ninth nodes, corresponding to Figure 3b, which is inversely similar to Figure 3f, where the nodes with the highest CP values were the locations with the lowest cellulose content. This is important because the less cellulose content the forage plant has, the more interesting it is, as it has more protein and, consequently, greater increases in animal weight.

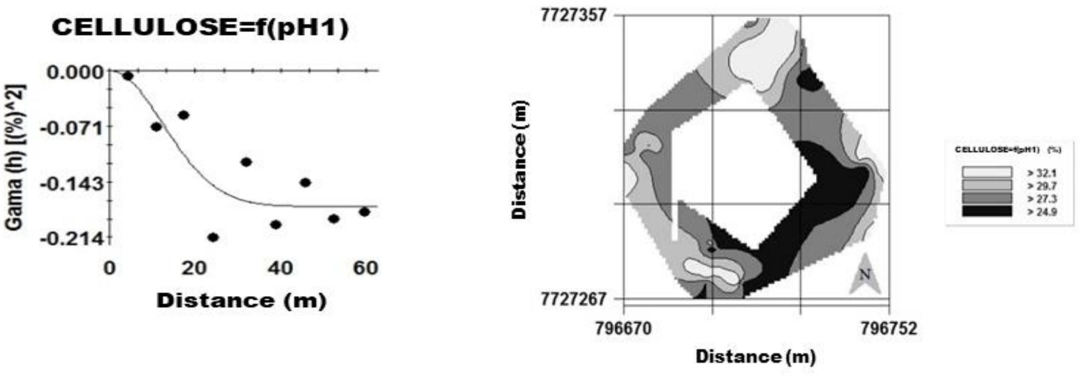
Looking at it from the other side, figure 4 shows maps of the spatial distribution of six attributes, however highlighting the four forage quality attributes: (a) Forage Dry Mass (DMF, (b) Crude Protein (CP), (c) Neutral Detergent Fiber (NDF), and (d) Acid Detergent Fiber (ADF), it can be said that the darker areas on the maps indicate a greater concentration of each attribute, representing the spatial variation in the area studied. The analysis reveals a non-uniform distribution of attributes influenced by soil type, moisture, fertility, management practices, and grazing history. Areas with high DMF tend to have lower CP, suggesting that a higher biomass yield may dilute the protein content. Areas with high NDF generally have high ADF, indicating lower forage digestibility and energy value.

This spatial variation allows for adjustments in management practices to optimize animal production. For example, areas with high DMF and low CP may require protein supplementation, while areas with high NDF and ADF can be used during periods of lower nutritional demand. Rotational grazing is an effective strategy for better using the different forage qualities. Based on the co-kriging maps between plant and soil attributes (Figures 5a and 5b), it is important to highlight the direct spatial correlation between HEI x OM_2, which shows that there will be an increase in eucalyptus height with an increase in OM.

It also showed an indirect correlation between Cellulose x pH_1, with a decrease in pH leading to an increase in cellulose, which is not interesting, thus showing the need to correct the acidity of the soil in places with lower pH values, creating specific management zones, which could even involve the application of lime at varying rates. Overall, the results point to the strong influence of soil properties on vegetation development. Eucalyptus growth correlates positively with soil organic matter content up to a saturation limit, indicating its crucial role in soil nutrition and structuring. The spatial heterogeneity of organic matter influences the yield potential of eucalyptus.



(a)



(b)

Figure 5. Crossed semivariogram and co-kriging map of (a) eucalyptus height (HEI) according to the organic matter content in the 0.10-0.20 m soil layer (OM2) and (b) forage cellulose content (CELLULOSE) according to the hydrogen potential (pH) in the 0.00-0.10 m soil layer.

In contrast, the cellulose content in forage is negatively impacted by an increase in soil pH, affecting its digestibility and nutritional value. The spatial variability of pH also influences forage quality. These results reinforce the need to consider soil heterogeneity to optimize crop management and drive the planting. Thus, according to Lima et al. (2022), kriging and co-kriging maps are important for precision agriculture, as they will later be analyzed and worked on to plan new samples and conduct fertilization with greater accuracy, providing greater savings, according to the spatial variability of the values of each attribute evaluated.

4. Conclusions

From a spatial point of view, eucalyptus height can be efficiently estimated through co-kriging using organic matter and cellulose through hydrogen potential. Organic matter content values above 6 g cm^{-3} indicated sites with higher eucalyptus heights, highlighting the importance of organic matter for developing these plants. The pH values below 4.3 are associated with higher cellulose contents in forage crops, indicating that soil acidity directly influences the bromatological composition of forage crops, implying the need to manage soil acidity to optimize forage quality properly. Using geostatistical tools proved technically feasible and beneficial for creating specific management zones in silvopastoral systems integrating eucalyptus and forage crops.

Authors' Contribution

Nilton Eugénio Mário: Conceptualization, preparation of graphs and tables, data interpretation, writing, and manuscript revision. Adriany Rodrigues Corrêa: Data collection, laboratory data analysis, and manuscript revision. Rafael Montanari: Statistical analysis of data, preparation of graphs and tables, data interpretation, and manuscript revision. Tatiane Carla Silva: Data interpretation and manuscript revision. Anderson Secco dos Santos: Data collection and interpretation and manuscript review.

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